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LESS OR DIFFERENT ENVIRONMENTAL IMPACT?

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INTRODUCTION

Electric and hybrid drivetrains are currently regarded as a promising technology for vehicle propulsion. They can reduce greenhouse and other exhaust gas emissions from road transport. Electric drivetrains are more efficient than conventional internal combustion engines fuelled by petrol or diesel (Chapter 5), and fully electrified vehicles does not give any tailpipe emissions. In addition, electric drivetrains can also assist in decoupling the transport sector from its heavy reliance on fossil fuels. On the other hand, electric vehicles will require that more electricity is produced and this can be done from several different energy sources with diverse environmental impacts. Furthermore, electric drivetrains require new advanced components (Chapter 3) that result in additional, or at least different, environmental impacts compared to conventional vehicles.

The trade-off between the benefits when operating of the vehicle and possible negative impacts from the production and from energy supply can be analysed using life cycle assessment (LCA). However, LCA studies come in many shapes and diverging arguments on the utility of technology are based on them. Some advocate the technology (using for example the well-to-wheels approach to guide government promotion policies on different types of drivetrains and alternative

fuel options)¹ and others claim that the prospective for electric cars to reduce the environmental impacts of mobility is “substantially overrated”² or that there will be “significant increases in human toxicity”.³

This chapter provides an overview of the life cycle impacts of electric vehicles, with general conclusions and examples of results. We review existing research and sort studies found in literature into categories by asking what we can learn from different LCA approaches. More specifically, which answers do we get from well-to-wheels (WTW) studies in comparison to complete LCA studies, and what difference does it make if a study includes a narrow or broad set of environmental impacts. We conclude by summarising these learnings and discuss implications for a set of stakeholders identified in the area of vehicle electrification, such as policy makers and various branches of industry.

LIFE CYCLE ASSESSMENT OF ROAD VEHICLES

LCA is a systemic tool for evaluating the environmental impacts of goods and services. It includes technically surveying all stages of a product's life cycle – from material acquisition and manufacturing to use and disposal. Data is gathered for inflows in terms of raw materials and energy, and outflows of products, emissions and waste at each stage. By linking the processes from cradle to grave, a system model is constructed to describe how flows are connected and influence one another. The overall result is an inventory of inflows to the system in terms of natural resources and outflows in terms of emissions to the surrounding natural system. The inventory is then analysed to evaluate various categories of potential environmental impacts, such as global warming, human toxicity and acidification.

LCA can be applied to vehicles in different ways. The WTW study is one type of LCA, which focuses on the life cycle of the energy carrier used to propel the vehicle, such as liquid fuel or electricity, rather than the life cycle of the vehicle itself (Figure 6.1). However, the vehicle operation is considered in the step where the energy carrier is used to propel the vehicle, called ‘tank-to-wheels’ (TTW).⁴ The stage before this, entitled ‘well-to-tank’ (WTT), focuses on the delivery of energy to the vehicle. It involves all processes from harnessing a primary energy flow or stock to different forms of energy conversion, distribution and storage. The environmental burden of the WTT phase varies depending on how the energy carrier is produced. For example, the difference is large between electricity produced from hydropower and coal fired plants. A WTW analysis is performed by connecting the WTT and TTW phases, as illustrated in Figure 6.1. In the case of liquid fuels, the TTW phase includes both exhaust and evaporative emissions. For pure electric vehicles charged from the grid, the TTW phase involves no emissions at all.

1 Ou, X. et al. (2010). Alternative fuel buses currently in use in China: Life-cycle fossil energy use, GHG emissions and policy recommendations. *Energy Policy*, 38, pp. 406-418.

2 Frischknecht, R. and Flury, K. (2011). Life cycle assessment of electric mobility: answers and challenges – Zurich, April 6, 2011. *The International Journal of Life Cycle Assessment*, 16, pp. 691-695.

3 Hawkins, T. R. et al. (2013). Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *Journal of Industrial Ecology*, 17, pp. 53-64.

4 In Chapter 5, the term grid-to-wheels (GTW) is used to examine electric vehicles' energy efficiency. GTW accounts for charging losses that affect energy efficiency but do not influence the environmental impacts of the operation phase.

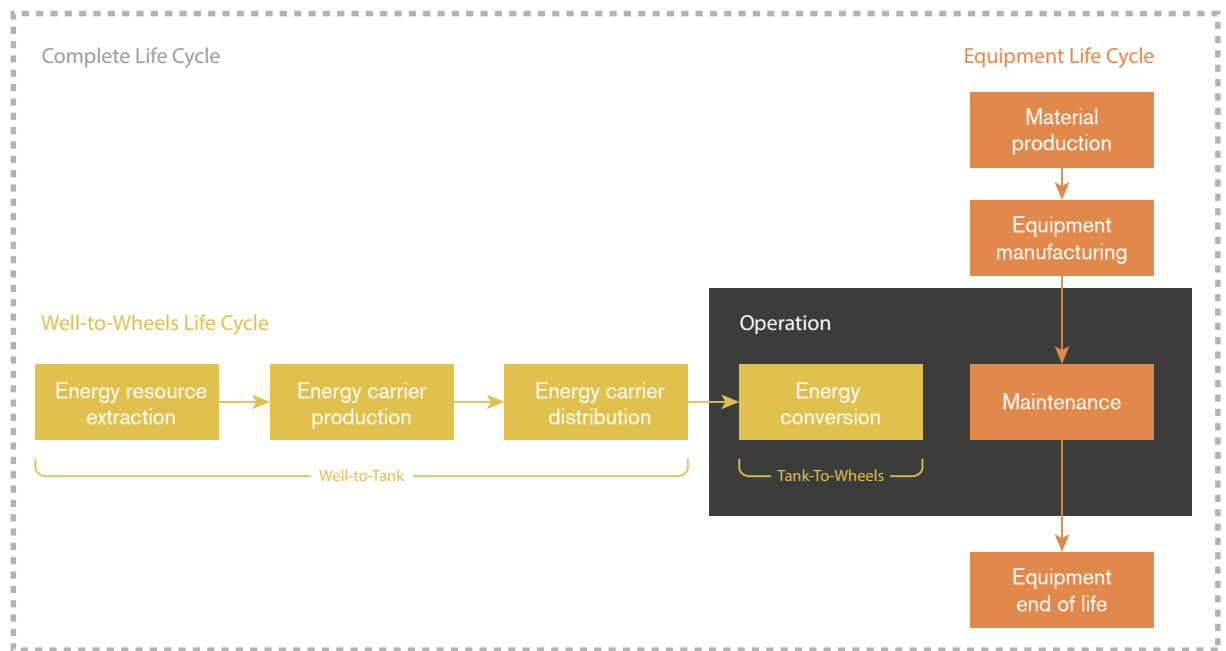


Figure 6.1 Simplified view of the well-to-wheels and equipment flows.

The vertical flow in Figure 6.1 represents the life cycle of the vehicle itself, which is sometimes referred to as the ‘the vehicle cycle’.⁵ In this text we use the term ‘equipment life cycle’, which is more general in that it is also applicable to both individual components and the drivetrain. This way of dividing the complete life cycle into two main flows is common in vehicle LCA and for studies where all processes are included, i.e. both the WTW and equipment life cycles, the term ‘complete LCA’ is used hereinafter.

The first phase in the equipment life cycle consists of raw material extraction and material processing. It is followed by manufacturing where parts are fabricated and assembled into a vehicle. The subsequent activity is the vehicle operation where the energy carrier and equipment cycles overlap. However, some aspects of the operation are solely connected to the equipment life cycle, namely service and reparation, shown in Figure 6.1 as maintenance. The final phase (end-of-life) includes dismantling the vehicle, recovering and recycling parts, and shredding and disposing of residues.

Table 6.1 is a compilation of 65 scientific articles, conference papers, government agency reports and reports published by other organisations that have conducted life cycle assessments of electric and hybrid vehicles. They are divided into three groups: WTW studies, complete LCAs and battery LCA studies. The table provides an overview of the research field and what the different groups of studies covers in terms of vehicle types and impact assessment. The term ‘functional unit’ refers to the entity used to assess the life cycle data (e.g. 1 km of driving). Note that the assumed vehicle lifetime (in km) differs widely between studies that perform complete LCA, and that the majority of studies focus on light passenger vehicles and greenhouse gas (GHG) emissions.

⁵ See for example Messagie, M. et al. (2010). *Life cycle assessment of conventional and alternative small passenger vehicles in Belgium*. 2010 IEEE Vehicle Power and Propulsion Conference, VPPC 2010. 1-3 Sept. 2010, Lille: IEEE.

Table 6.1 An overview of the scope of publications on LCA of electric and hybrid vehicles from 1998 to early 2013. The main share consists of scientific articles (43 titles) and conference papers (11 titles) and the remaining titles are different types of reports and books.

Articles / Category	WTW study	Complete LCA	LCA of Batteries ^a	TOTAL
FUNCTIONAL UNITS	1 km of driving	1 km of driving 1 vehicle life (95,000-560,000 km)	1 km of driving 1 kg battery 1 kWh battery	
TECHNOLOGY				
<i>Light duty or passenger vehicles</i>	18	30	5	53
<i>Other vehicle types^b</i>	3	2	8	13
<i>Externally chargeable</i>	18	27	13	58
LEVEL OF IMPACT ASSESSMENT				
<i>Global Warming (GHG)</i>	19	32	4	55
<i>Energy</i>	9	14	8	31
<i>Broader assessments^c</i>	8	17	9	34
TOTAL	20	32	13	65

^a Equipment life cycle or complete LCA of batteries.

^b In the case of battery studies, this means that no vehicle type has been specified

^c Studies including several impact categories and emissions besides GHGs and energy.

WHAT CAN WE LEARN FROM WELL-TO-WHEELS STUDIES?

Drivetrain electrification can potentially reduce GHG emissions by increasing the TTW efficiency and by making it possible to abandon energy produced from fossil fuels in the WTT phase. For externally chargeable vehicles such as battery electric and plug-in hybrid electric vehicles (BEVs and PHEVs), GHG emissions depend on the entire WTW life cycle. Consequently, it is common to adopt the WTW perspective when the purpose of a study is to assess the efficiency of different drivetrain options; to assess the climate impacts of different energy carriers; and to examine how electricity production influence vehicles' environmental performance (see Chapter 8 and 9 for wider system implications via links to other sectors).

In a large WTW study commissioned by the European Union, externally chargeable electric vehicles in the compact class were compared with conventional vehicles. The study focused on GHG emissions, based on the standard European driving cycle (NEDC).⁶ Three categories of vehicles were defined: PHEVs, BEVs and so-called 'extended range electric vehicles' (E-REVs). The data used in the study was based on prototypes and development vehicles with batteries and electric motors in a range of different sizes⁷ to provide a worst-maximum case and a best-minimum case for each category. All use of liquid fuel was limited to petrol. The PHEV category has limited electric performance and an electric driving range of 20-40 km, with start-up in either pure electric or blended hybrid mode. The

⁶ Edwards, R. et al. (2011). *Well-to-Wheels Analysis of Future Automotive and Powertrains in the European Context – Well-to-Wheels Appendix 2 Version 3C, WTW GHG-Emissions of Externally Chargeable Electric Vehicles*. EUR – Scientific and Technical Research series – ISSN 1831-9424. July 2011, Luxembourg. (ISBN 978-92-79-21395-3, reported by Joint Research Centre of the European Commission, EUCAR and CONCAWE).

⁷ See Chapter 3 for a discussion on different EV components and configurations.

E-REV category refers to vehicles driven by the electric motor but they have an internal combustion engine that is used to generate electricity for the battery and thus extend the driving range of the vehicle. The BEV category includes vehicles propelled entirely by externally-produced electricity. The study excludes auxiliary energy use by applications such as air conditioning and lighting (see Chapter 5). These vehicles are compared to a 'reference' case based on conventional petrol driven vehicles.⁸

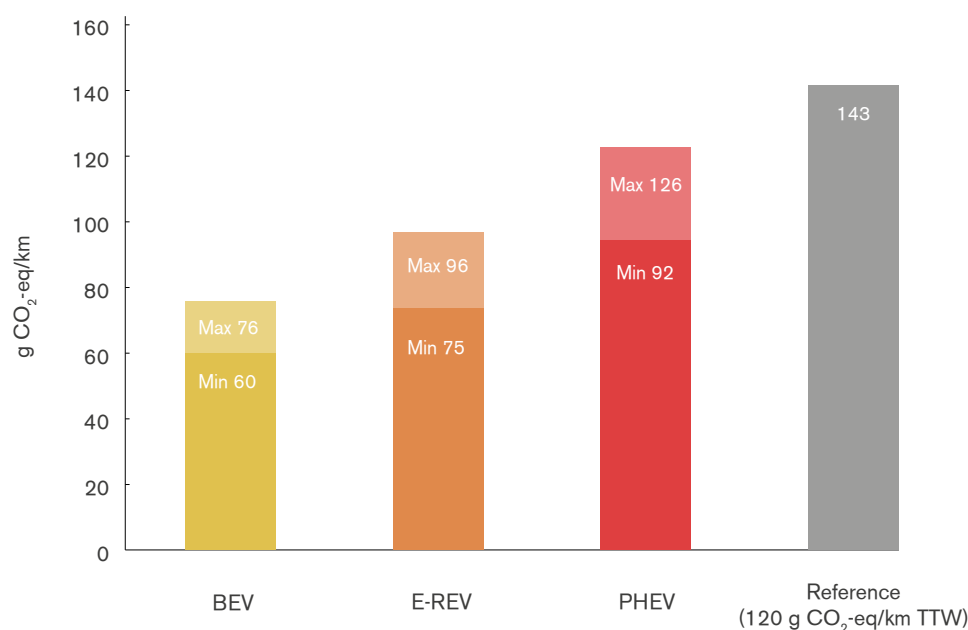


Figure 6.2 WTW GHG emissions based on an average EU electricity mix (467 g CO₂-eq/kWh). The reference vehicle corresponds to a former EU fleet target for tailpipe emissions of new sold cars. Source: Edwards et al. (2011), Position of the European Parliament (2008).

Figure 6.2 shows the results of the WTW analysis based on the average EU electricity mix (467 g CO₂-eq/kWh for 2008). As can be seen, all electrified vehicles have lower emissions than the reference case. The data also demonstrates a reduction in GHG emissions with an increasing degree of electrification, although the different vehicle categories overlap with regard to minimum and maximum values. However, Figure 6.2 does not show that overlaps are larger for higher electricity GHG intensities. At intensities greater than 900 g CO₂-eq/kWh (which corresponds to oil-fired electricity) even the BEV category starts to emit more than the reference vehicle.⁶

Figure 6.3 shows how different electricity production gives altered WTW GHG emissions for a small, family-sized BEV. It is clear that carbon intensive fossil electricity production results in strikingly higher emissions than nuclear or renewable electricity, also when the impacts of power plant construction are considered.⁹ Equally noteworthy is that electric vehicles that run on oil- and coal-fired electricity have life cycle emissions similar to the tailpipe emissions of modern diesel and petrol cars.

⁸ Conventional petrol-driven vehicles with tailpipe emissions of 120 g CO₂-eq/km. Tailpipe emissions refer to the TTW phase and correspond to 143 g CO₂-eq/km for the full WTW.

⁹ Electricity production is treated as a 'background system' to the foreground technology that is studied. See Figure 10.2 in Systems Perspectives on Biorefineries 2013 for another example of the importance of background systems.

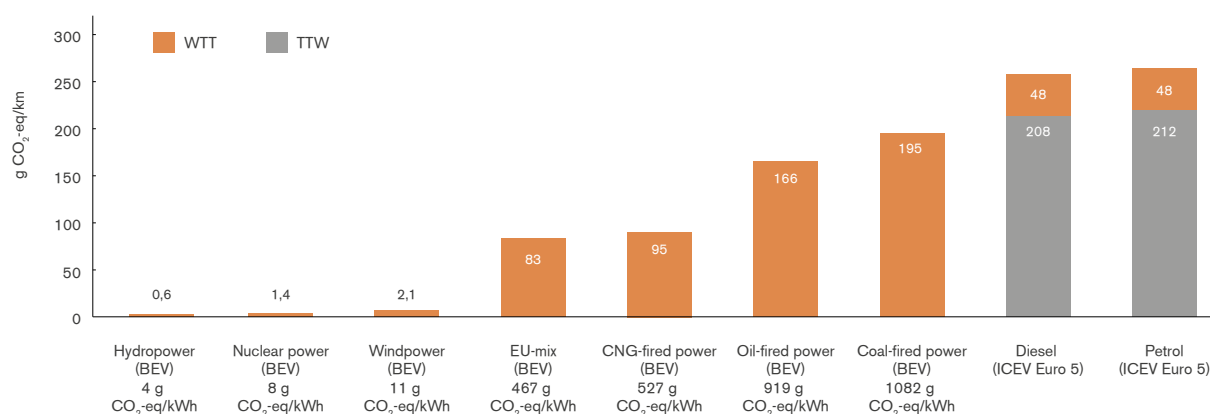


Figure 6.3 WTW GHG emissions for the small family car segment with different types of energy production (with the construction of the power plants included). Reference vehicles correspond to the average Euro 5 vehicles for petrol and diesel in the same segment in Belgium at the time of the study. Source: Messagie et al. (2010)

A vehicle classified as 'small family-sized' is roughly of the same size as one classified as a 'compact car', i.e. they belong to the same size class or segment. However, the conventional petrol- and diesel-fuelled reference vehicles in Figure 6.3 correspond to average values of the Belgium vehicle fleet, whereas the reference in Figure 6.2 correspond to a fleet target value for new sales in EU¹⁰. Nevertheless, passenger cars come in many different sizes and vehicle weight is a key factor for environmental performance.² This is important to have in mind when one is analysing results of various studies. Table 6.2 shows typical vehicle segments and corresponding representative vehicles. BEVs are usually classed as city or compact cars and PHEVs are usually classed as family vehicles, whereas and HEVs (Hybrid Electric Vehicles) can be found in all segments.

Table 6.2 Typical conventional light passenger vehicles divided into groups of established segments with similar vehicle size.

Segments grouped according to size	Examples	Electric categories
City cars / Mini vehicles	Fiat Punto, Citroen C1, Peugeot 106, Smart	HEVs, BEVs
Compact cars / Small family cars	Volvo C30, Ford Focus, VW Golf, Nissan Leaf	HEVs, BEVs, PHEVs
Executive compact cars / Family cars	Volvo S40/V40/V60, Toyota Prius	HEVs, PHEVs
Executive cars / Large family cars	Volvo V70/S80, Ford Mondeo,	HEVs, PHEVs
Small monovolumes / Small multi-purpose vehicles	Ford Focus C-Max, Opel Zafira,	HEVs, PHEVs
Monovolumes / Multi-purpose vehicles	Ford Galaxy/S-Max, Peugeot 807	HEVs
Luxury cars	Lexus LS, Mercedes S-Klasse,	HEVs
Sport Utility Vehicles	Lexus RX, Mercedes M-Klasse	HEVs

WTW studies can also be used to assess the impacts of different modes of operation and vehicle control strategies. Typically this could be the impact of different driving styles and traffic situations. Figure 6.4 shows an example of such a

¹⁰ This former target of 120 g CO₂-eq/km has been rephrased into a mandatory fleet value for the type approval per manufacturer of 130 g CO₂-eq/km by 2015.

WTW study, which examines the GHG emissions of a conventional petrol vehicle compared to a HEV and a PHEV operating in different traffic conditions.¹¹ The study is limited to large family cars and with similar specifications. The results for three driving modes are shown. City driving refers to slow driving with many starts and stops in highly congested city traffic. Suburban driving refers to a scenario with less congestion, allowing higher speeds. Highway driving refers to a scenario with high speeds and no stops. The results show that the hybridised drivetrains are beneficial in congested traffic as there are many stops, which allows for regenerative braking to recover energy. At a standstill, conventional vehicle engines are kept idling whereas in hybridised vehicles they are automatically turned off (see Chapter 5 and Figure 5.1).

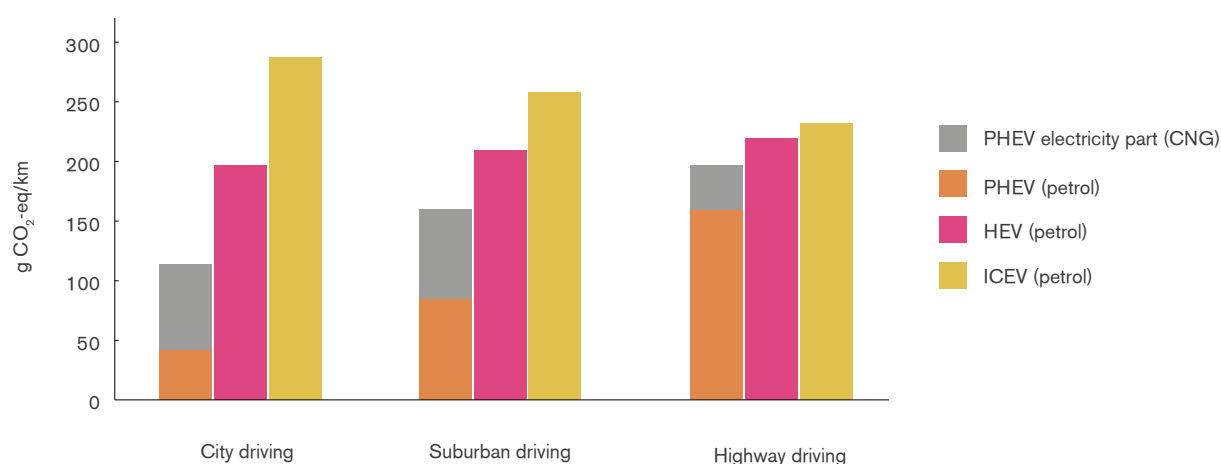


Figure 6.4 WTW GHG emissions for three types of large family petrol vehicles in three traffic situations. The data for the PHEV is based on charging with electricity produced from natural gas. Source: Raykin et al. (2012)

Reflecting a bit on the use of the WTW studies, it should be pointed out that when data is presented for an all-electric vehicle charged with low carbon electricity, it might give the impression that electric vehicles have no environmental burden at all. This is not true. In other cases, WTW studies are used to compare the climate impacts of vehicles in very diverse segments (see Table 6.2). In both these cases it can be argued that a complete LCA would add valuable insights.

WHAT CAN WE LEARN BY INCLUDING THE EQUIPMENT LIFE CYCLE?

Including both the WTW chain and the equipment life cycle as part of a complete LCA can provide a more comprehensive mapping of vehicles' environmental impacts. Vehicles of different sizes but with similar fuel consumption can be compared with more relevance because drivetrain sizing and composition are included in the assessment. Figure 6.5 shows the overall lifetime GHG emissions per kilometre for some well-known brands and models in four different segments. The data is based on NEDC-certified fuel consumption rates and an average EU electricity mix. The general trend is, as expected, that larger vehicles have higher emissions and that emissions decrease as the vehicles get smaller. Notable is that the HEVs have low emissions in each segment and that the small family-sized BEV has the lowest lifetime GHG emissions, also when compared to the smaller city

¹¹ Raykin, L. et al. (2012). Implications of Driving Patterns on Well-to-Wheel Performance of Plug-in Hybrid Electric Vehicles. *Environmental science & technology*, 46, pp. 6363-6370.

segment. However, in this case vehicles in different segments are stipulated to have the same lifetime in terms of driven kilometres, which can be disputed.

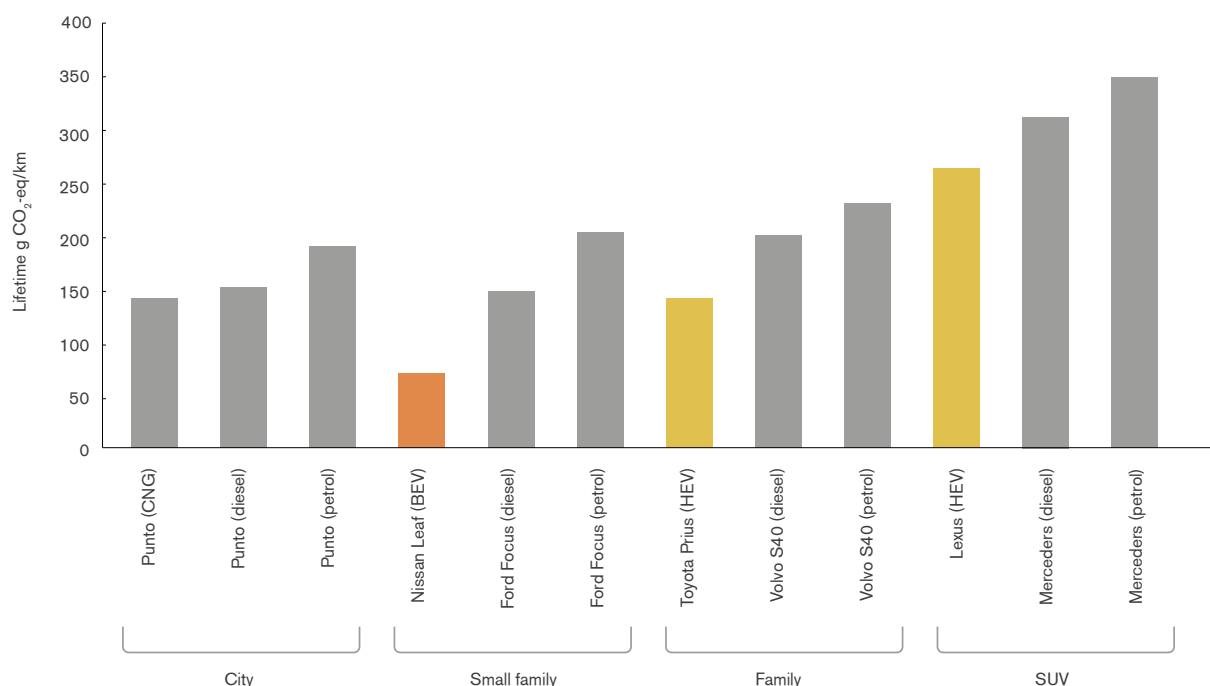


Figure 6.5 Life cycle CO₂-emissions for passenger cars divided into typical segments showing the general trend in CO₂-emissions for the full life cycle. An average vehicle lifetime of 230500 km corresponding to 13.7 years has been used, based on statistical data from the Belgian vehicle registration database. Fuel consumption is based on NEDC data. The Nissan Leaf BEV has been assumed to run on the EU electricity mix. Source: Messagie (2012).

A general rule of thumb may be established by comparing the complete life cycle results with the earlier WTW results. It is that vehicle operation is the dominating stage with regard to energy use, both for conventional vehicles and those with electrified drivetrains. However, many studies point out that the relative importance of the manufacturing stages increases with electrification. This is due to the reduction of emissions (in absolute numbers) from the WTW cycle as well as the introduction of new components. A study made in the UK which includes the full life cycle of light passenger vehicles, provides some typical results. It indicates that the GHG emissions are coming in approximately equal shares from the WTW life cycle of the energy carrier and equipment life cycle of the vehicle, see Figure 6.6. In this case it is a BEV driven in urban conditions, and charged with a projected average grid mix in the UK. However, the WTW share of the total GHG emissions becomes dominating as soon as more fossil intense electricity is considered or the driving scenario is set to highway or suburban. Another observation is that vehicles of different types, segments and brands have different life lengths both in terms of total driving distance and years of operation (see Table 6.1). For this reason it is important to review and question the assumptions made for the total amount of kilometers driven whenever complete life cycle results are presented per kilometer.

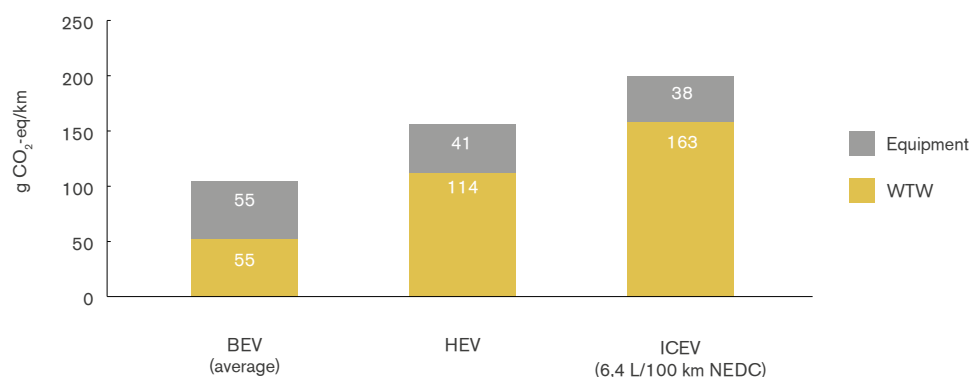


Figure 6.6 GHG emissions from the WTW cycle and the equipment cycle in a UK urban driving scenario with low speed and load (15 years lifetime and 12000 km/year). Electricity is based on a projected UK, mix corresponding to 450 g CO₂-eq/kWh. Source: Ma et al. (2012).

It can also be pointed out that electric drivetrains can be realized in many different configurations and that the components in general are immature for automotive application (see Chapter 3). This implies that there is both a large span from the best to worst case, and that various assumptions made during the course of the LCA may play an important role. It is also very important to remember that there is a large improvement potential for the future.

Summing up, by adding the equipment and WTW life cycles a more complete assessment is achieved. This is useful when vehicles with similar WTW performance, but different degree of equipment complexity, are analysed and compared. It also gives better understanding of where focus should be put for further improvements. The WTW phase often plays a dominating role for the emission of GHG. As long as it does, keys to improvement of environmental performance will be to minimise the demand for fossil fuels in the WTT phase and to increase efficiency in the TTW phase. Nevertheless, the addition of the equipment life cycle perspective provides information about the roles of the different components and the effects of changes in the drivetrain.

WHAT CAN WE LEARN FROM A BROADER IMPACT ASSESSMENT?

So far this chapter has reflected only upon environmental aspects connected to the use of energy and emissions of GHG. However, there are also other resources and emissions which are relevant to include if the aim is to establish a more comprehensive description of the environmental performance of electrified vehicles. For a life cycle assessment to be regarded as extensive and complete, it should cover the impacts on three important areas of protection: natural environment, natural resources and human health (see also the discussion on horizontal system delineation in Chapter 1 in Systems perspectives on Biorefineries).¹²

LCA results may also be presented in different formats. For example, the inventory format (detailed resource use and emission categories) is useful when the target audience is well informed about the substances emitted from the product chain.

¹² ISO (2006). Environmental management - Life cycle assessment - Principles and framework (ISO 14040:2006). 2006-10-05 2006, Geneva, Switzerland: International Organization for Standardization.

This is the case of the automotive industry, which is familiar with the regulated tailpipe emissions – carbon monoxide (CO), unburned hydrocarbons (HC/VOC), nitrogen oxides (NO_x) and particulate matter (PM). However, there are also numerous other substance flows including resources and non-regulated emissions. Furthermore, these flows may interact in complex manners. This is why life cycle impact assessment (LCIA) is often conducted. LCIA aggregates emissions contributing to the same type of environmental effect into one indicator and likewise for resource use. Aggregation can be done all the way to one single number, a one-dimensional measure of the environmental impact. However, whatever weighting method is used to achieve this, it will include a large number of contested value judgements. Therefore, so called ‘mid-point’ indicators are often used. These aggregate the inventory results into a limited number of impact categories.

A typical such midpoint indicator is the already frequently shown global warming potential (GWP) reporting all GHGs as CO₂-equivalents. Another is the photo-oxidant creation potential (POCP) which describes the local air pollutants that build up smog under the influence of sunlight and harm both human health and growing crops. The eutrophication potential (EP) covers the effect of macronutrients in soil and water (including NO_x). The acidification potential (AP) indicates the potential environmental impact of acidifying substances such as NO_x and sulphur oxides (SO_x). The results may also be further aggregated into so called end-point indicators, describing effects on e.g. human health and biodiversity.

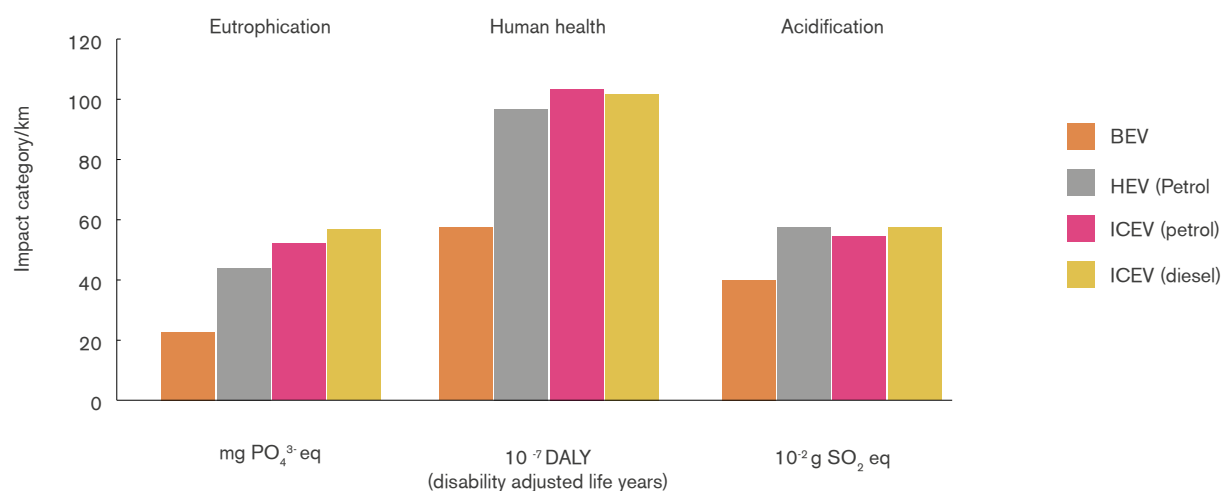


Figure 6.7 Results for the eutrophication (left), human health (middle) and acidification (right) impact categories in an LCA of small family vehicles in Belgium. The BEV is equipped with a lithium ion battery charged with the Belgian electricity mix. The HEV has a NiMH battery and a Euro 4 emission standard engine. The conventional references for petrol and diesel are both of Euro 5 standards. Sources: Messagie et al. (2010) for eutrophication and human health and Boureima et al. (2012) for acidification. Eutrophication and acidification characterization factors according to CML (2002). Human health characterization factors according to Jolliet et al. (2003).

Figure 6.7 shows examples of LCA results presented as LCIA indicators. They are based on the same data as those presented in Figure 6.3, but this time for the Belgian electricity mix. A BEV and a HEV in the small family-size segment are compared with conventional references. LCIA results are shown for eutrophication, acidification and an endpoint impact indicator summarizing the overall damage potential for human health. As can be seen, the trend is that the impact

decreases with increased electrification and this applies to all impact categories, just as in the case of GHG emissions. The explanation for this covariance is that all the shown types of impacts are caused by airborne pollutants which mainly are coupled to combustion, either in the vehicle or at a power plant. Consequently, the results for externally chargeable vehicles are strongly dependent on the electricity production and the overall efficiency of the WTW life cycle.

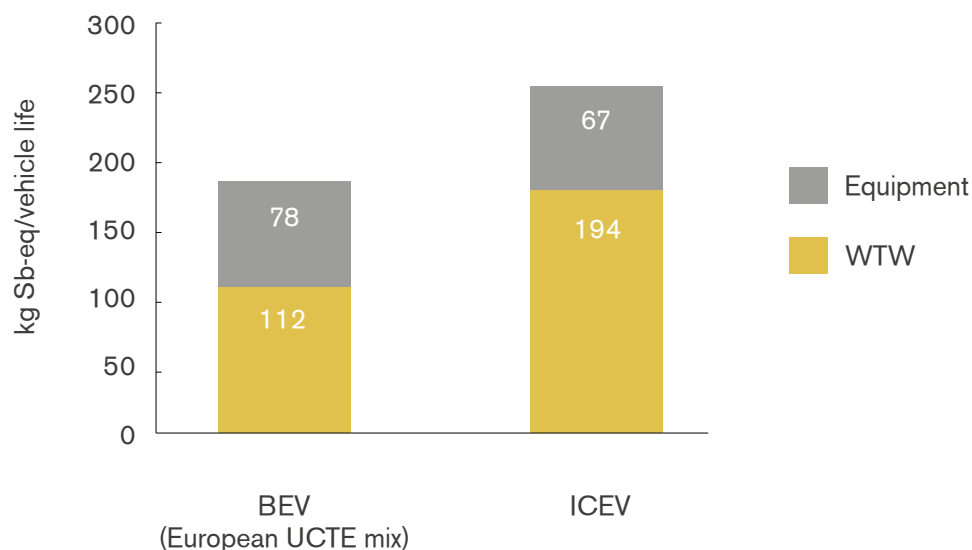


Figure 6.8 Results for the abiotic resource depletion impact category for two different version of a vehicle in the compact class divided into the WTW and equipment life cycles. The BEV is charged with a part of the European electricity mix referred to as UCTE (596 g CO₂-eq/kWh and 4.4 g Sb-eq/kWh). Source: Notter et al. (2010).

All indicators discussed so far relate to emissions of pollutants. However, LCA aspires to also include resource use. The use of abiotic resources may be aggregated into an indicator for abiotic resource depletion potential (ADP). It covers non-living resources such as metals and oil. An example is shown for an ICEV and a BEV in the compact class in Figure 6.8. It displays abiotic resource depletion in terms of antimony equivalents (kg Sb-eq). Although the use of metal resources in the vehicle cycle is higher for the BEV, this is still outweighed by the larger use of the fossil energy reserve by the ICEV, according to the study. However, worth mentioning is that the ADP used in the example is based on estimates of the global reserves of each mineral combined with their extraction rates. By now these are 10-15 years old. As a consequence, high scores are given for fossil energy depletion in comparison to copper, nickel, lithium and rare earth metals relevant for electric and hybrid vehicles. Other resource use indicators provide much higher values on copper and nickel, but still relatively high values on fossil fuels and do often not cover lithium and rare earth metals.¹³ (See Chapter 7 for a more in depth analysis of electric vehicles and metal resource constraints)

¹³ See for example Goedkoop, M. J. et al. (2012). *ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level*. Report I: Characterisation. First (revised) ed. July 2012.

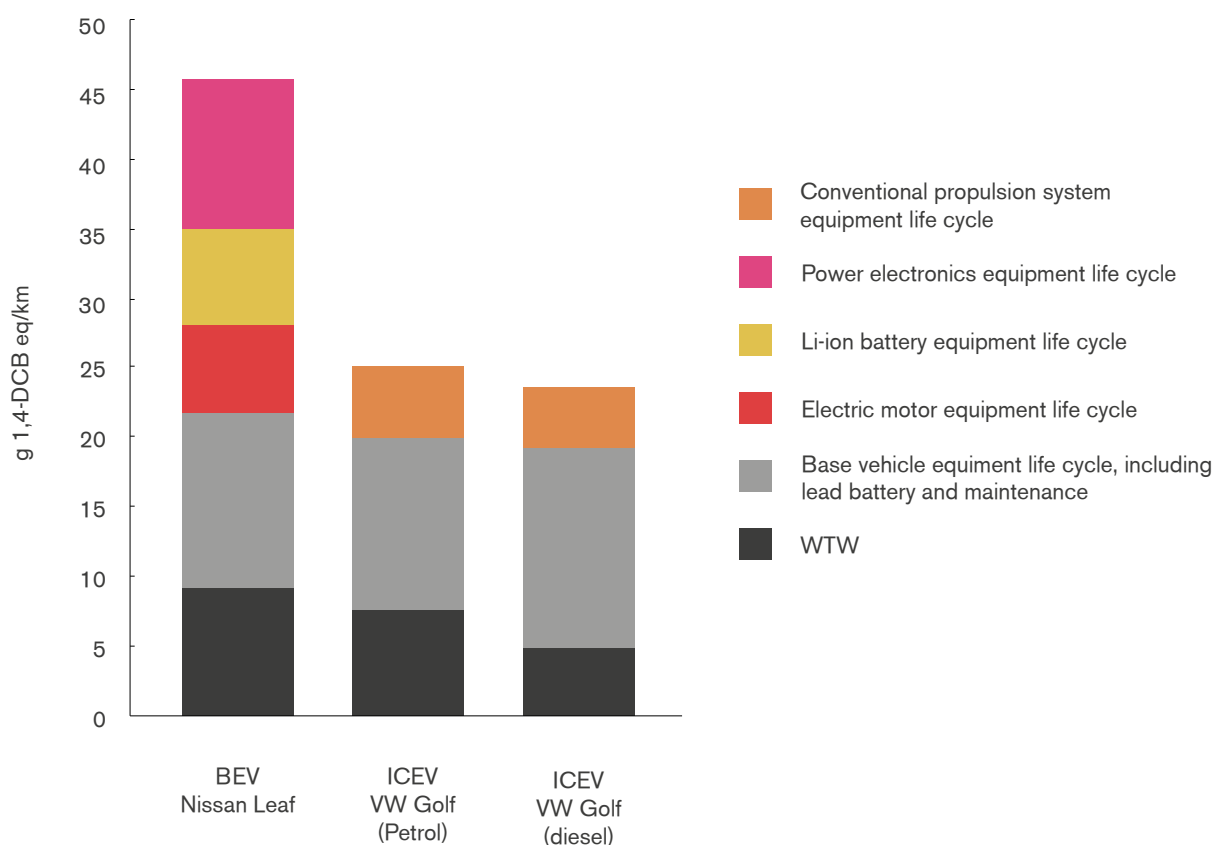


Figure 6.9 Results for the human toxicity potential comparing compact class vehicles for different drivetrain options. A vehicle life distance of 209470 km has been assumed and the BEV is charged with the Belgian electricity mix. All use of petrol and diesel are of Euro 5 standard. Sources: Messagie (2013) (manuscript). Characterization factors according to Goedkoop et al. (2012).

Local emissions of toxic substances from the manufacturing stages are an environmental aspect which has been brought up in some studies as a possible disadvantage of electric drivetrains, especially in connection to battery production. Figure 6.9 presents the human toxicity potential (HTP) in units of 1,4-dichlorobenzene, a well-known pesticide. It indicates significantly higher impact with respect to toxicity from BEVs than conventional vehicles. A very important part of the explanation to the HTP results in Figure 6.9 is mining processes, both in the production of electricity and components. The big difference revealed for WTW phase has its cause in leakage from the mining spoils of coal and lignite for electricity production. And the larger equipment life cycle emissions of the BEV refer to disposal of sulphides in mine tailings. It is coupled to increased use of copper and nickel, both in the battery and the electric motor, and copper and gold in the power electronics. Improved waste handling in the mining industry and a less coal dependent energy mix could therefore dramatically change these results.

Furthermore, toxicity is a complicated impact category. It accounts for many different substances and their inherent toxicity, along with the potential that humans and/or ecosystems are exposed to the substances in a manner that cause adverse effects. This impact category is generally coupled to a high degree of uncertainty due to its dependence on various background conditions and the need for very large data sets in the assessment.

To this point only studies modelling the whole vehicle, or at least the drivetrain, with a similar level of detail have been described. A different, but also quite common approach is to set the focus on a single component such as the battery, either in the context of a full vehicle LCA or more specifically in a component LCA study. The reason is that there is a consensus among all studies that the traction battery is a key component in terms of weight, performance and durability.¹⁴

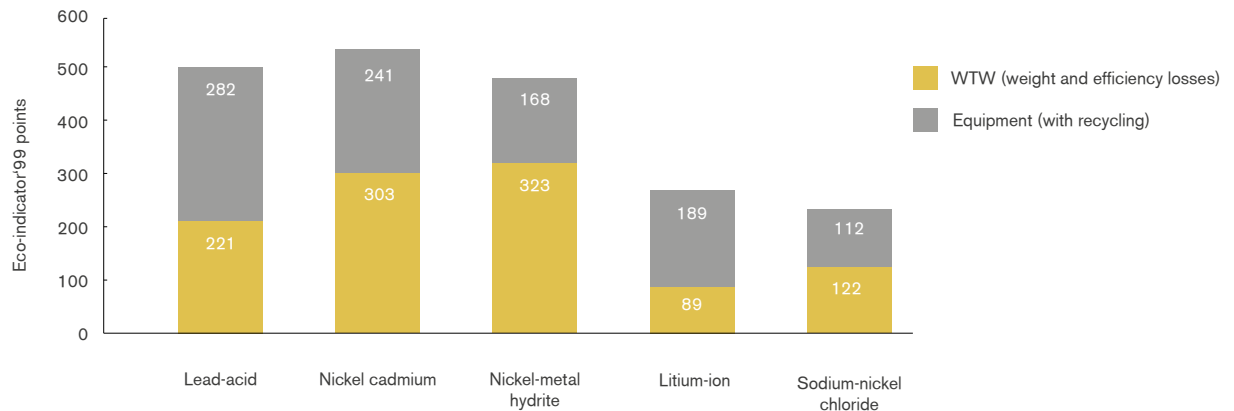


Figure 6.10 Eco-indicator'99 net results (credited for recycling) for the environmental score of different battery types – all dimensioned to provide 60 km range at an 80% depth of discharge for an 888 kg electric car (excluding the weight of the battery) and a vehicle life distance of 180 000 km with 3000 charge-discharge cycles. The WTW phase corresponds to the amount of electricity needed to cover for internal losses and to carry the weight of the battery itself, based on a European mix. Source: Van den Bossche et al. (2006)

Figure 6.10 shows the scores of different battery types for a fully electric compact car according to a panel-based weighting system named Eco-indicator'99.¹⁵ It is possible, as mentioned above, to aggregate LCA results to one single score in order to analyse the trade-off between benefits in several impact categories and drawbacks in others. Different impact categories are then weighted based on societal values and summed up. It shows that the high energy density and low system losses of the lithium-ion and sodium-nickel chloride technologies are rewarded with low scores. Recycling is important for the results for all battery types – high collection rates and that almost all material can be recovered with virgin material quality has been assumed in the study. For the newer technologies this means that an entire new recycling industry must come into place on a large scale if these results are to be realized (see Chapter 7 for a critical discussion on this assumption).

Another thing to bear in mind when reading results from traction battery LCAs is that battery technology is progressing very rapidly. A consequence is that data for environmental performance very quickly get outdated. Evidence of this is that in studies conducted around 2005 it was common to assume one or even two battery replacements over an average vehicle life time, while today it is often argued

¹⁴ See for example Frischknecht and Flury (2011). Life cycle assessment of electric mobility: answers and challenges – Zurich, April 6, 2011. *The International Journal of Life Cycle Assessment*, 16, pp. 691-695.

¹⁵ LCA impact assessment can be performed to achieve a single scale for all categories – to provide support for the interpretation of the results. Eco-indicator'99 is such a method where the weighting principle is based on the average damage a certain environmental load causes in Europe.

that the battery will last as long as the vehicle.¹⁶ At the same time critical steps in the manufacturing have also been improved. Finally, technology development also change which battery types that are considered relevant and therefore included in the study in the first place.

Summing up, impact assessment beyond GHG can be conducted to very different degrees, from a couple of selected additional emissions in inventory format to more than ten different aggregated impact categories or even further to a weighted result. However, with regard to emissions of airborne pollutants in general, it turns out that the values for GHG is a good overall indicator for all related impact categories. On the other hand, impact categories related to resource extraction, such as abiotic resource depletion and toxicity, provide new information and indicate that further in depth analysis is needed.

REFLECTIONS AND CRITICISMS

Traditionally, LCA is a tool for analysing the environmental burden of a reasonably well defined and mature product or service, for all stages of its life cycle. However, key traits of emerging technologies, such as electric propulsion of road vehicles, are that they have not yet reached the level of maturity and scale that they show potential for. The examples given in this chapter show that most assessments focus on the performance of today's electric vehicle technology used in today's electricity production system. Still, both vehicle technology and electricity production may be expected to have changed considerably before the vehicle volumes are comparable to those of ICEVs. Furthermore, improvements in the production, both due to progress in manufacturing technology and benefits of scale, may decrease the future environmental load significantly in different equipment life cycle stages.

As an alternative, LCA can be regarded as a tool for strategic assessments of a technology. It is then less relevant to examine the environmental performance in the current state of development, in contrast to some future state where the technology has reached its full potential.¹⁷ This time aspect is relevant not only for the actual vehicles and components, but even more so for the electricity production mix. As shown, all impact categories are dependent on the WTW electricity and in most cases this is the dominating factor. Most studies today are designed to answer a set of specific questions based on the current electricity production and technology level. The numerical results provided are then particular for the given context and study format. Consequently, there is a risk to be misled if too much focus is set on detailed results and less on the very varying input. Instead is important that LCA studies identify and also broadcast the one crucial message on which all studies show consensus – for externally chargeable electric vehicles to reach their full potential to help mitigate global warming, the electricity production must be made clean and free from emissions of fossil carbon (see also Chapter 2, 5 and 8).

¹⁶ See for example Zackrisson, M. et al. (2010). Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles - Critical issues. *Journal of Cleaner Production*, 18, pp. 1517-1527.

¹⁷ See Hillman, K. M. and Sanden, B. A. (2008). Time and scale in Life Cycle Assessment: the case of fuel choice in the transport sector. *International Journal of Alternative Propulsion*, 2, pp. 1-12.

Nevertheless, given the different results presented in this chapter it should also be pointed out that some impact categories are more well-established than others and generate more robust results. Those relating to the vehicle tailpipe emissions, such as global warming, are very robust. In all such categories electric drivetrains show clear benefits to conventional ones. In the case of human toxicity there are many uncertainties related to data availability and aggregation procedure. At the same time, there is reason to heed the signal from LCA studies, however uncertain, and try and minimise use of mineral resources and leakage of toxic substances from mine tailing. The risk of problem shifting from emissions related impact to impact related to dependence on certain metals is further discussed in Chapter 7. The direct risks related to handling vehicles (such as risk for explosion) is not normally part of LCAs, but could in principle be weighed against the more indirect toxic effects that are included. The direct risks related to handling are discussed in Chapter 4.

Another observation, which is also reflected in this chapter, is that almost all scientifically published LCA studies concern cars for individual transportation. Other vehicle types such as heavy duty trucks and buses remain to be more fully explored (see Chapter 14 on the perspective of freight transport companies). It should also be pointed out that the vehicle end-of-life generally is not so well mapped. Effective recycling of materials with high quality is currently difficult to achieve. At the same time, a high degree of recycling is necessary, again, for these vehicles to reach the environmental performance they show potential for.

As a final reflection, the holistic perspective of LCA is a key to its usability as a learning tool. For example, it can help identify dependencies and relationships which are not obvious at first, such as the dependency on electricity production system and the need for efficient recycling.

CONCLUDING REMARKS

This chapter has presented different setups for LCA studies on electric and hybrid vehicles. It has discussed how the answers provided depend on both the technical and methodological scope. WTW studies demonstrate that greenhouse gas emissions from vehicles in general are reduced with increased electrification of the drivetrain, but the main conclusion is that this improvement is heavily dependent on the fossil content of the electricity mix. As a consequence, assuming that BEVs and PHEVs will constitute a large share of all vehicles only in the long term, power companies and policy makers must acknowledge that electrifying vehicles with external charging capability make their task of enforcing fossil free electricity production, on a global scale, even more urgent and important.

In addition, WTW studies also show that the driving behaviour and traffic situation is important. Electrified drivetrains are most beneficial in city traffic with a lot of driving at slow speed. This is a perfect match with the built-in reduction of local tailpipe emissions and limited range. Moreover, complete LCA studies point out an increased importance of the equipment life cycle, indicating that it is most beneficial to make use of electric drivetrains in vehicles that are intensively used (see Chapters 10 and 11 for the economic version of the same argument). This

conclusion may be of importance to policy design as well as strategies in the automotive sector, e.g. which market sectors that should be targeted with incentives and investments, and how the size of electric and combustion drivetrains should be balanced in PHEV designs.

Studies providing more extensive impact assessment mainly confirm the important role of the electricity production. However, with regard to toxicity issues, environmental agencies and policy makers as well as the automotive and power industries should be aware that aspects related to mining possibly can become an environmental area of attention in the future. Efforts made to improve these practices are beneficial also for hybrid and electric vehicles.

Moreover, policy makers, the automotive industry and the recycling industry should learn that establishing a proper recycling system for lithium batteries and other components is yet another key to success. It is, in fact, a necessary condition for technology diffusion beyond minor niche markets. It can also be noted that the current LCIA of resources accentuates fossil energy and does not reveal depletion of minerals such as lithium or rare earth metals which may become critical for electric and hybrid vehicles in the future (Chapter 7).

Finally, it may be concluded that the answer to the main question of this chapter is that electrified passenger cars already today generally gives less environmental impact than their conventional counterparts. These results are robust and supported by a large number of publications. In this context, LCA may then be regarded as a learning tool giving the possibility to identify important improvement areas in striving for increased sustainability of electrified vehicles.